THEME II: EARTHQUAKE RISK ASSESSMENT AND LOSS ESTIMATION

Earthquake Loss Estimation Methods, Models and GIS. Robert V. Whitman, Professor of Civil Engineering, Massachusetts Institute of Technology

EARTHQUAKE LOSS ESTIMATION METHODS, MODELS AND GIS

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Abstract

A typical earthquake loss estimate covers a range of economic and social losses expected from a specified hypothetical "scenario earthquake." Such estimates are potentially of value for preparedness and disaster response planning, for stimulating and planning mitigative actions to reduce future losses, and for analysis of insurance exposure. High-speed desk top computers, and geographic information systems (GIS) for dealing with large data files, have made possible more comprehensive loss estimates, including wider ranges of structural types, components of lifeline systems, economic losses (including long-term regional impacts), casualties and shelter requirements, and volumes of debris. A variety of computer software has been developed. Some of it is proprietary. FEMA has developed a comprehensive methodology (HAZUS) for use by states, regions and communities. However, such increased comprehensiveness means much greater effort and cost to assemble the required inventory. At the same time, scientific knowledge concerning the relations between ground motions and damage, between damage and economic losses, between building damage and casualties, etc. has advanced only slowly and hence the accuracy of loss estimates is limited. Major policy questions include: 1. How to choose appropriate "scenario earthquakes?" 2. What are the appropriate trade-offs among accuracy, comprehensiveness and cost? 3. What level of government should pay for loss estimates? 4. How can loss estimates be used to stimulate mitigation?

I Topic Description and Policy Issues

Reliable estimates of losses from future earthquakes potentially are of great value in preparedness and disaster response planning. Loss estimates are the basis for preparing scenarios describing the state-of-affairs in a city or region following some specified earthquake: extent and location of damage to buildings and other facilities, the extent of casualties, the likelihood of fires, functionality of essential facilities and of transportation and utility lifeline systems. Loss estimates may also be used to stimulate and guide efforts to mitigate the effects of earthquakes through improved building practices and land use regulations. For example, the decrease in losses as a result of mitigative actions can be estimated[1].

Loss estimates have broader uses than described here. Industries and governmental agencies with very large facilities can use estimates in connection with preparedness, response planning and mitigation studies. The insurance industry has developed several methodologies for its own use, and for estimating Probable Maximum Losses for compliance with some state regulations. Owners of a single building, facility or lifeline system can make effective use of a loss estimate.

Technology for accomplishing comprehensive loss estimates exists today. The accuracy, completeness and usefulness of any estimate depends upon the effort devoted to assembling the required data. For an ideal loss estimate, the effort potentially is quite great. It is necessary to collect information concerning the inventory of populations, buildings and lifeline facilities, and the important characteristics of this inventory. Detailed information concerning local soil conditions is required. For certain buildings and facilities whose size and nature imply especially great potential for casualties and economic losses, detailed engineering studies may be necessary to establish reliably the likelihood for these losses. If the resources available for all these efforts are limited, the resulting loss estimate will be less accurate and complete and may as a result be less useful.

Even the best loss estimates now possible will have potential shortcomings. The exact location of future earthquakes, and the details of the ground shaking they cause, are inherently uncertain. Ground motions, and the damage they cause, depend upon details of local soil conditions that are extraordinarily difficult to establish. Current scientific knowledge concerning the performance of the vast number of different types of buildings is still very scant. The resulting uncertainties increase as the resources available to construct a study decrease. These uncertainties may be especially significant where studying benefits of possible mitigative actions.

These observations lead to several policy issues:

1. How complete and accurate must a loss estimate be if it is to be useful as a basis for preparedness and disaster response planning, and as a basis for justifying mitigative actions?
2. What is the potential for using loss estimates to guide decisions concerning mitigative actions to reduce losses from future earthquakes: building codes, land use regulations and remediation of hazard existing buildings and facilities?
3. What are appropriate trade-offs between the accuracy and completeness of loss estimates vs. the cost of performing such studies?
4. Should there be a uniform standard for all loss studies?
5. Who should pay for loss studies?....cities?...states?....national government?

II <u>Background</u>

Figure 1 shows the major components of an earthquake loss estimate, and indicates the flow of information among the components. Basically, there are five major steps:

1. Defining the geographical region to be covered by the loss estimate, and selecting the earthquake for which losses are to be estimated. The earthquake is defined by magnitude and location. Only one earthquake is considered per analysis, but the effects of different magnitudes and locations may be studied through repeated analyses.

2. Evaluation of ground motions that the earthquake causes within the region. This involves identifying local soil conditions that can affect the intensity of ground motions, and evaluating permanent ground displacements that may result from shaking -induced liquefaction and landsliding.
3. Assembling an inventory of buildings, lifeline transportation and utility systems, and other constructed facilities, and establishing the key characteristics of the inventoried items as related to susceptibility to damage during earthquakes. The inventory task also includes collection of data relative to population and its distribution, and several types of economic data.
4. With this information assembled, the next step is to evaluate the expected damage to buildings and other facilities as a result of the estimated ground movements. Such damage may lead to additional hazards that will cause further losses - such as flooding as a result of failure of dams or dikes, and from fire. (There may also be damage as a result of tsunamis and seiches.)
5. Then the losses resulting directly from the damage are evaluated. These losses may include the cost of repair or replacement of damaged buildings structures and other facilities, including damage to contents and inventory; economic consequences of interruption of service, including loss or rental income, business relocation, etc.; fatalities and injuries; shelter requirements; and quantity of debris to be removed. In the process, information of special interest for disaster response planning is generated, such as: expected number and likely locations for fire ignitions, possible releases of hazardous substances, and extent of flooding. Finally, given the various direct economic consequences of damage, changes in the economy of the affected region may be projected for a number of years following the earthquake.

Preparation of regional earthquake loss estimates for large metropolitan regions of the United States began about 2 decades ago, and the methodologies used for these studies has evolved over that period. The very recent years since the Loma Prieta (1989) and Northridge (1994) Earthquakes have seen rapid advances.

Development of a nationally-applicable methodology, incorporating standardized procedures for computing damage and losses plus a number of national data bases as a starting point for the inventory effort, has been funded by the Federal Emergency Management Agency (FEMA) - and will be ready for trial use by regional and local governments early in 1977. The methodology is known as HAZUS, and some aspects of this methodology will be discussed subsequently. One aim of this effort was to advance the state-of-the-art in loss estimation, and to develop a general methodology that can deal with diverse parts of the constructed infrastructure and can expand to make use of new data as it becomes available. Although computational procedures are standardized, HAZUS permits great flexibility in the use of its capacity.

The insurance industry has also been particularly active in developing methodologies for loss estimates, and results are used in setting insurance rates and in high-level discussions concerning the possible need for governmental intervention in natural-hazards-related insurance. The general framework of the methodologies used by insurers is known, but many details - including important inventory data bases - are proprietary.

It is important to note that the technology for estimating losses caused by possible future earthquakes may also be used for rapid estimation of losses following an actual earthquake; the only special requirement is to have immediately available a suitable inventory of constructed facilities for the affected region.

The following subsections discuss key steps in the process of loss estimation, as background for understanding of policy issues and to identify aspects of the technology that can especially benefit from additional, focused research drawing upon experience and expertise in both Japan and the United States. Comprehensive loss estimates do involve considerable complexity, and some understanding of some technical details is essential. One message should be clear: The ability to perform calculations leading to estimated losses, and knowledge concerning earthquakes and the ground motions they cause, greatly outstrips the scientific base of knowledge concerning the effects of ground motions upon the many different types of buildings, other structures, facilities and lifeline systems.

Selection of scenario earthquakes: This step requires effective interaction among earth scientists and officials in city and regional governments that are to use the results of the loss estimate. When it is anticipated that results will be used to move forward with mitigative actions, is also important to include leaders from the private sector that must make the investments necessary to reduce future losses.

In a highly seismic region, where very large earthquakes have occurred and hence can be expected again, local officials and the business community generally will be comfortable with assuming the "maximum credible earthquake," although loss evaluations for smaller but more frequent earthquakes may also provide useful information. In less seismic areas, choosing a large earthquake with a very small annual probability of occurrence may not be most appropriate for disaster response planning, and can lead to feelings of helplessness as regards steps to reduce possible future losses. Hence very careful thought must be given to selection of scenario earthquakes in these regions.

Recent decades have witnessed major advances in understanding of earthquake mechanisms and of recurrence frequencies. It is important that current international co-operation in such research continue.

Ground motions resulting from scenario earthquake: Until HAZUS, loss estimation methodologies have used Modified Mercalli Intensity (MMI) to characterize the strength of ground shaking. MMI is a non-quantitative measure of shaking, based upon the degree and extent of damage to conventional residential buildings and personal reactions. MMI was a very useful scale in earlier days when relatively few actual recordings of ground motions were available. However, saying that, for example, MMI = 8 does not provide information adequate for assessing the expected response of lifelines, large buildings and a broad range of building types.

At the outset of the development of HAZUS, a decision was made to switch to a quantitative description of ground shaking, using measures familiar to engineers who analyze constructed facilities. The engineering response spectrum was selected for this purpose[2]. Nationally-recognized "attenuation laws" are used to calculate ordinates of the response spectrum as a function of distance from the epicenter of the specified earthquake. These ordinates are further modified, again using a nationally-recognized method, to account for local soil conditions.

In addition to damaging structures and lifelines directly, ground shaking may cause soil to lose strength and thus settle or move laterally as landslides - a phenomenon known as "liquefaction." Landslides can occur on steep slopes in rock as well as on non-liquefying slopes in soil. All such permanent displacements can cause great damage to structures and lifeline systems. HAZUS incorporates procedures for estimating the amount of settlement and lateral permanent displacement that may be experienced by various types of soil and rock.

The "attenuation laws" and the rules for estimating liquefaction and landsliding caused permanent displacements are based primarily upon measurements and observations made during the major earthquakes of the last two decades, augmented by theory. However, the available data are still inadequate for allowing accurate predictions of transient and permanent ground motions as a function of the types of soil or rock at a site. In recent years there has been good co-operation between Japan and the United States in the exchange of ground motion recordings - and it is vital that this co-operative effort continue.

Inventory: The major task in a loss estimate is preparation of the inventory of the constructed facilities in the study region and of the people and organizations that occupy and use these facilities. The inventory potentially must include buildings, essential facilities (medical facilities, fire stations and emergency operation centers), lifelines (highways and other transportation systems; electricity, potable water and other municipal utilities; communication systems), and facilities and structures the failure of which might cause very large economic and social consequences (dams, certain industries, very large buildings, etc.)

A response spectrum is a plot of the peak response of a single-degree-of-freedom mass-spring-dashpot system vs. the natural period of the system, for a specified damping. The information contained in this spectrum can be used to evaluate the dynamic response of complex multi-degree-of-freedom structures.

Since typically there will be many thousands of buildings in the region being studied, it is impractical to identify and analyze each building individually. Hence the general building stock is generally grouped into occupancy and building type classes - each potentially containing a large number of buildings. Similarly, simplified procedures are used to inventory many aspects of lifeline systems. Essential facilities and facilities with high potential for losses may be inventoried individually.

For buildings, HAZUS uses a census tract as the basic geographic region. In using HAZUS, buildings must first be classified into 28 occupancy classes (various types of residences, various types of commercial organizations, etc.). Information concerning the occupancy of buildings is contained in the national census and in data bases maintained by major financial institutions, and this information has been used to construct default tables for HAZUS - giving the square feet of floor area for each occupancy class in each census tract. A user of HAZUS May (and usually should) modify these tables based upon locally-available information.

Buildings are then classified further into 36 model buildings types, according to height and structural system - those characteristics having a primary influence upon behavior during earthquakes. Users of HAZUS can further sub-divide each model building type with regard to the level of seismic design and general quality of construction. Information concerning structural systems generally is not readily available in data bases, even those that have been complied locally. HAZUS contains several default table applicable to different regions of the United States, that are suitable for rough, preliminary loss estimates. At a minimum, use should be made of knowledge of local engineers and architects concerning the building stock, to customize these tables for a study. Buildings of particular interest, such as essential facilities, can be entered into HAZUS as individual buildings.

Assembling the inventory of lifelines and their components is an even larger and more difficult task. There are some useful, national data bases - such as those for highway bridges, which are included in HAZUS. However, these sources include little if any information concerning those characteristics that most effect susceptibility to damage during earthquakes. It is essential to make maximum use of locally-available information, and secure cooperation from governmental and private-sector utilities.

The foregoing detail regarding the development of an adequate inventory has been set forth to emphasize the complexity of the challenge. There is need for continued research to improve and make more efficient the technology for transforming locally-available information into methodologies such as HAZUS. The challenge is amplified because data bases generated for other purposes tend to vary in character and content from one community to another. However, ideas as to how this transformation can best be made are transferrable across international boundaries - and here is a potential area for co-operation between Japan and the United States.

<u>Evaluation of damage to buildings and other structures:</u> The key in this step is establishing relationships, for each model building type, between ground movements and

damage. Damage is described in terms of "damage states" - written descriptions of damage as related to different model building types. For a very few types of buildings - such as wooden-framed homes built following California practice - there exists enough data from actual earthquakes to develop reasonably satisfactory empirical relationships. Expert judgment has been relied upon to recommend relationships for other building classes. HAZUS makes use of a simplified theoretical procedure that is grounded upon experience and the limited information from laboratory testing programs. To some extent it has been possible to benchmark these relationships against performance observed during earthquakes, but this type of data is very sparse.

Lack of the inadequate scientific base for relating damage to ground movements is perhaps the most significant shortcoming of HAZUS and all other loss estimation methodologies, and is a major contributor to uncertainty as to the reliability of loss estimates. It is vital to seize every opportunity to benchmark the damage prediction methodology embedded within HAZUS against experiences during real earthquakes. Even though construction practices differ in Japan and the United States, Japanese earthquakes can be used to learn more about the accuracy of this damage prediction methodology. A focused collaborative effort between researchers in the two countries would allow such efforts to proceed much more rapidly.

Evaluation of damage to essential and high potential loss facilities: The approximate procedures for estimating damage to the general building stock do not necessarily give a reliable estimate of damage when applied to an individual building. While HAZUS permits this to be done, results must be interpreted with great care. This is especially true of a very large building with thousands of occupants, where slight adjustments to the relation between damage and casualties can make an enormous difference in the estimate of casualties for a region. With such high potential loss facilities, it is desirable to have a detailed analysis and study, based upon a rigorous method of dynamic analysis. Performing such an analysis requires ascertaining considerable information concerning the structure, experienced engineering expertise, and - most important of all - the wholehearted cooperation of the owner of the structure. HAZUS does not contain the software to support such an analysis. However, results from a detailed study may be imported into HAZUS and combined with losses estimated by the methodology for the general building stock.

Performance of lifelines: HAZUS and other general loss estimation methodologies evaluate damage to components of lifeline systems. For highways, this means damage to bridges, possible damage to stretches of pavement because of liquefaction or landsliding, and damage to tunnels.For an electric power system, the principal components likely to be damaged are electrical sub-stations. For potable water systems, pipelines may be damaged by both transient and permanent ground displacements. HAZUS contains algorithms for the relationships between ground motion and degree of damage, based upon the scant available data from studies of actual earthquake experiences plus theoretical considerations. Because empirical information concerning components of lifeline systems is relatively sparse compared to that for buildings, estimates of damage to lifelines are less reliable than those for buildings.

There exists methodologies for analyzing the overall performance of a lifeline system. These systems typically have many redundancies; for example, if highway bridges are closed by damage in one portion of the system, traffic flow within most of the total system can still be maintained - perhaps at a reduced level - by rerouting traffic through sub-areas that escaped damage. Similar statements apply to water and electrical systems, etc. Such analyses, like those for individual structures, require special software, considerable information concerning the system being studied, special engineering expertise, and the cooperation of the owner and operator of the system. HAZUS does not contain software to permit such analyses, but results from independently performed studies may be imported into HAZUS for combining with other results.

As with buildings, for further progress in loss estimation it is vital that all available data concerning the performance of lifeline components during earthquakes be assembled and analyzed. The existing good co-operation between researchers in Japan and the United States should be enhanced.

Evaluation of economic and social losses: The final steps involve relating various types of losses to the estimated degrees of damage for various model building types and components of lifelines. These depend upon empirical data gleaned from observations following earthquakes. HAZUS contains values for the necessary conversion factors, but again the data are so scant as to give rise to considerable uncertainty in estimated losses. Monetary costs perhaps can now be estimated within bounds that are adequate for many purposes. However, agencies using loss estimates ask for more reliable estimates of fatalities and other casualties. Here is another area where focused collaborative efforts between Japan and the United States can make the process of interpreting available information proceed much more rapidly and efficiently.

HAZUS also has the capability to estimate the functionality of lifeline components vs. time following an earthquake, but these estimates are highly dependent upon realistic input from the potentially affected communities concerning capacity for effecting repairs.

Fire following earthquake: HAZUS includes software for estimating the number of ignitions caused by an earthquake, and the extent of the spread of fires. The types of construction, the size and density of city blocks, and the width of streets are factors accounted for by the software. The estimates for spreading depend upon local input concerning capacity for fighting fires, and upon such locally-selected parameters as wind speed and direction. Because these local factors can be so variable, HAZUS does not estimate actual fire-related losses, such as casualties or even the most likely monetary losses, but rather the monetary value and populations exposed to predicted fire-affected areas.

It will be valuable to have co-operative efforts to test and hence improve the models for ignition and fire spread using experiences in both countries.

Evaluation of regional economic effects: HAZUS includes software for evaluating the impact of an earthquake upon various sectors of a regional economy. The model uses information concerning the monetary losses incurred by these various sectors at the time of the earthquake, the flow of funds from outside to assist with reconstruction and recovery, the likelihood that affected industry and commerce may relocate elsewhere, etc. Although the economic principles underlying this model are well-recognized among economists, application of them to earthquakes is new, and there has been as yet little opportunity to test the model against actual experiences.

This is a potentially very important aspect of earthquake loss prediction, but it seems premature for any focused cooperative efforts between Japan and the United States.

Computerization and use of GIS systems: Estimation of losses for a region requires many, many repetitive calculations, and hence computerization of a methodology is virtually essential. Use of Geographic Information Systems (GIS) potentially offers many benefits with regard to the assembly and display of data for the inventory, and for display of results. The problem is that different communities are using different (and also various versions of) GIS software. Conversions between one system and another are in principal possible, but often fraught with difficulties. HAZUS has used the GIS system MAPINFO as the shell within which all the software operates. It is anticipated that versions based upon other GIS shells (especially ARCINFO) will be developed.

Presumably time, experience and economic incentives will reduce these difficulties without major governmental intervention

III Proposals

1. There appears to be a significant mismatch at present between the hopes and desires of users of loss estimates as regards completeness and accuracy (and cost of producing an estimate) and the actual degree-of-completeness and accuracy that can now be achieved with acceptable costs. It is very important that all interested parties reach a clear understanding in these matters. This understanding should be based a upon careful assessment of the current scientific base of factual information, and also upon how much the scientific base can expand as a function of time. These matters are important to both Japan and the United States, and to policy makers and loss estimation specialists from both countries.

    A bi-national group involving policy makers and loss estimation experts should meet a sufficient number of times to arrive at recommendations concerning at least the first four policy issues stated in Section 1.

It is not at all clear just what effective use has been made of loss estimates that have been produced during the past two decades in Japan and the United States; what influences they have actually had upon preparedness and response planning by local and regional governments; and to what extent they have actually influenced to pace and directions of mitigative efforts to reduce future earthquakes.

There should be a systematic study of the uses and influences of past loss predictions in both countries. The study should be led by social scientists experienced in the area of public policy related to natural hazards, but the team must also involve technologists to aid in putting the completeness and accuracy of the predictions in perspective.

3. There are several aspects of the scientific base that will benefit in the short run from focused efforts to extract all potentially useful information from past earthquakes. These aspects are: (1) The relationships between ground shaking and the degree of damage to various types of buildings and components of lifeline systems, and (2) The relationship between the degree and nature of damage experienced by various types of buildings and resulting fatalities and injuries.

Study groups with workers from both countries should be formed and funded to pursue the proposed efforts in an expeditious manner. Engineers should be the principal contributors to the first study. For the second study, medical personnel as well as engineers must be involved.

4. There is still much to be learned in the earth sciences and geotechnical engineering that can improve the accuracy and value of future loss estimates. Good interchange of information and of co-operation in specific studies has occurred in recent years, and to a large extent learning has kept up with the availability of data available from earthquakes.

Co-operative efforts already underway at the basic research level, dealing with earthquake mechanisms, ground motions resulting from earthquakes (including the influence of soil conditions) and earthquake induced geological hazards (liquefaction and landsliding) should continue to be supported - and where necessary be enhanced to ensure the rapid interchange between countries of data acquired in the aftermath of earthquakes.

IV. Cooperative Mechanisms

Since I am not well acquainted with existing cooperative mechanisms at the government-to-government level, I am unable to offer specific recommendations.

As regards the first proposal, there is potentially a major problem: The need to include representatives of the private sector, and especially from insurance companies. The loss estimation methodologies developed within the insurance industry are proprietary and there is a natural reluctance to release information concerning these methodologies. A review of policy matters at the government-to-government level can deal with issues concerning the use of loss estimates as regards preparedness and response planning. However, use of loss estimates to foster mitigative actions will always be clouded if there is inconsistency between losses evaluated by different methodologies.

The other proposals primarily involve researchers. While existing agreements appear to foster effective interchange of information, and have in the past formed a basis for joint research studies (I am most aware of the large-scale structural testing that was carried out cooperatively), it may be necessary to amend them to permit effective joint research efforts.

V. Related Issues

In the big picture, it is important to understand the risks from earthquake in the context of risks posed by other natural hazards. FEMA has expressed an intent to expand upon HAZUS to incorporate methodologies needed to estimate losses from wind and water. The general framework shown in Figure 1 is adaptable to all natural hazards, but it is not yet clear whether it is feasible to deal with all hazards within one system of software.

VI. Key References

The principal general reference concerning earthquake loss estimation is:

Estimating Losses from Future Earthquakes, Publication No. FEMA 177- June 1989, Federal Emergency Management Agency, Washington DC